

Naval Surface Warfare Center Carderock Division

West Bethesda, MD 20817-5700

NSWCCD-65-TR-2003/48 November 2003

Survivability, Structures, and Materials Department
Technical Report

Flexural Testing of Steel Wire Composite Beams Made with Hardwire™ Unidirectional Tape

by

Robert Matteson and Roger Crane



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DEPARTMENT OF THE NAVY
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9078
Ser 65/11-80
5 Jul 11

From: Commander, Naval Surface Warfare Center, Carderock Division

To: Chief of Naval Research (ONR 332)

Subj: HYBRID COMPOSITE JOINING AND CHARACTERIZATION PROGRAM

Ref: (a) Seaborne Structures Materials Program (PE 0602236N)

Encl: (1) NSWCCD-65-TR-2003/48, *Flexural Testing of Steel Wire Composite Beams Made with HardwireTM Unidirectional Tape*

1. Reference (a) requested the Naval Surface Warfare Center, Carderock Division (NSWCCD) to investigate the feasibility of new materials for use in marine composite structures. A new fiber material system, which can be used in composite manufacturing, trademarked *Hardwire*, was investigated. This material is a high-strength, continuous steel wire tape, which can be used in composite structures. Enclosure (1) presents results of mechanical tests conducted to determine material properties, which could be used in the design of a novel joint concept.

2. Comments or questions may be referred to Dr. Roger M. Crane, Code 655; telephone (301) 227-5126; e-mail, Roger.Crane@navy.mil.

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Enclosure (1)

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 18-Nov-2003		2. REPORT TYPE Final		3. DATES COVERED (From - To) -	
4. TITLE AND SUBTITLE Flexural Testing of Steel Wire Composite Beams Made with Hardwire Unidirectional Tape				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 0602236N	
6. AUTHOR(S) Robert Matteson and Roger Crane				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Naval Surface Warfare Center Carderock Division 9500 Macarthur Boulevard West Bethesda, MD 20817-5700				8. PERFORMING ORGANIZATION REPORT NUMBER NSWCCD-65-TR-2003/48	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Attn ONR 332 Chief of Naval Research One Liberty Center 875 North Randolph St., Suite 1425 Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A new fiber material system, which can be used in composite manufacturing, trademarked Hardwire, was recently developed. This material is a high-strength, continuous steel wire tape which can be used in composite structures. This paper presents results of mechanical tests, conducted to determine material properties which could be used in the design of a novel joint concept. Numerous configurations of Hardwire were tested. The parameters included fiber packing density, fiber twist, and surface coating. Because of problems in developing compression failures in end and shear loaded compression configurations, flexural tests were conducted. A three-point bending test was used to determine the apparent strengths and bending stiffness of the various Hardwire composite forms. The modification of surface treatment with both the Jeffco18 and Al74, resulted in improved strength and stiffness over unmodified wire. The amount of fiber twist significantly improved strengths. In fact, by increasing the lay length of the wire (decreasing the twist angle) failure mode changed from compressive buckling to a nearly ductile tensile failure.					
15. SUBJECT TERMS ship structures, composite materials					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 23	19a. NAME OF RESPONSIBLE PERSON Dr. Roger M. Crane
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code) (301)-227-5126

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Administrative Information

The work described in this report was performed by the Structures and Composites Division of the Survivability, Structures, and Materials Department, at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by the Office of Naval Research, Code 332, under the Seaborne Structures Materials Program (PE 0602236N) under the guidance of Dr. Ignacio Perez.

Acknowledgements

The authors would like to acknowledge the support of Mr. George Tunis from Hardwire LLC for his support in the manufacturing of the specimens used in this study and in his participation in the testing of these materials.

Purpose

The purpose of this test series was to determine the effects of varying processing changes on the apparent bending strength and modulus of unidirectional Hardwire¹ composite beams made with epoxy and vinyl ester resin. Flexural testing also provides a means of assessing the interfacial bond strength between the fiber and resin. Since the overall objective was to design and develop a novel hybrid joint, determination of these properties was essential.

Hardwire is a potential reinforcement for composite components for Navy applications. The initial primary interest for this material is in composite to metal joining applications. Here, the steel wire would be used as a transition between conventional steel plate and conventional composite. In this form, one end of the steel wire section would be welded to a steel plate with the other end processed into the conventional composite in scarf or stepped lap form and infiltrated with resin using a VARTM process. Hardwire could also be used as a high stiffness fiber for a high-strength hull or superstructure material to replace or augment glass or carbon composites. Composites made from Hardwire are up to 70% thinner and 25% lighter than composites made with glass fibers (as reported by Hardwire, LLC) and present excellent potential for primary Navy structures.

Background

Hardwire is a recently developed reinforcement product that consists of steel filaments, bundled into cords. These cords are spooled and used in a tape forming machine to produce 12 inch wide unidirectional continuous fiber tape. In this effort, this tape is being laminated to form a composite beam. It is infiltrated with a standard epoxy or vinyl ester material using a VARTM process. In addition to using the material in this form, it can be hybridized with other reinforcement materials, such as fiberglass or carbon fibers, to modify structural strength and stiffness. The steel wire used for the Hardwire product is a very high-strength and high-modulus steel, provided by Goodyear. The wire product provided to Hardwire is the same steel wire used for steel belts in automobile tires. As such, its mechanical strength and long term fatigue life has a proven history of in-service performance.

Goodyear has tested the individual steel fibers and has provided tensile strength and stiffness test values of 450 ksi and 30 Msi, respectively.² For the joint and structural

¹ Hardwire is a trademark of Hardwire LLC, 1000 Quinn Avenue, Pocomoke City, Maryland 21851; <http://www.hardwirellc.com/index.html>.

² Information available from <http://www.hardwirellc.com/Technical/tools.html>.

applications, it is necessary to determine how these mechanical properties translate into composite properties. One of the more informative test methods to determine if there are any adhesion problems is the flexural test. In this testing, any fiber adhesion problems are seen by the failure mode. If there is good adhesion, a tensile failure of the fibers is possible. If there is sub optimal adhesion between the steel fibers and matrix, there will be a shear failure or low maximum tensile stress in the outer fibers. In addition, the flexural testing is simple to perform both in sample preparation and actual mechanical testing.

Approach

All specimens were tested in accordance with ASTM D790, “Standard Test Method for Flexural Properties of Reinforced Plastics,” except where noted. Specimen sizes were large, having a span-to-depth ratio greater than 60 to 1. Because of the large deflections that were obtained in each test, the crosshead displacement rate was set at 0.1 in/min. It should be noted that this is higher than the rate specified in the ASTM D790. Deflection was recorded at the midpoint of the specimen via an Instron PD-1M deflectometer. However, since most of the test specimens experienced deflections greater than the maximum range of the deflectometer, subsequent calculations were made using data collected from a string potentiometer position sensor that was attached to the test frame. Figure 1 shows a typical time displacement curve using both the PD-1M and position sensor.

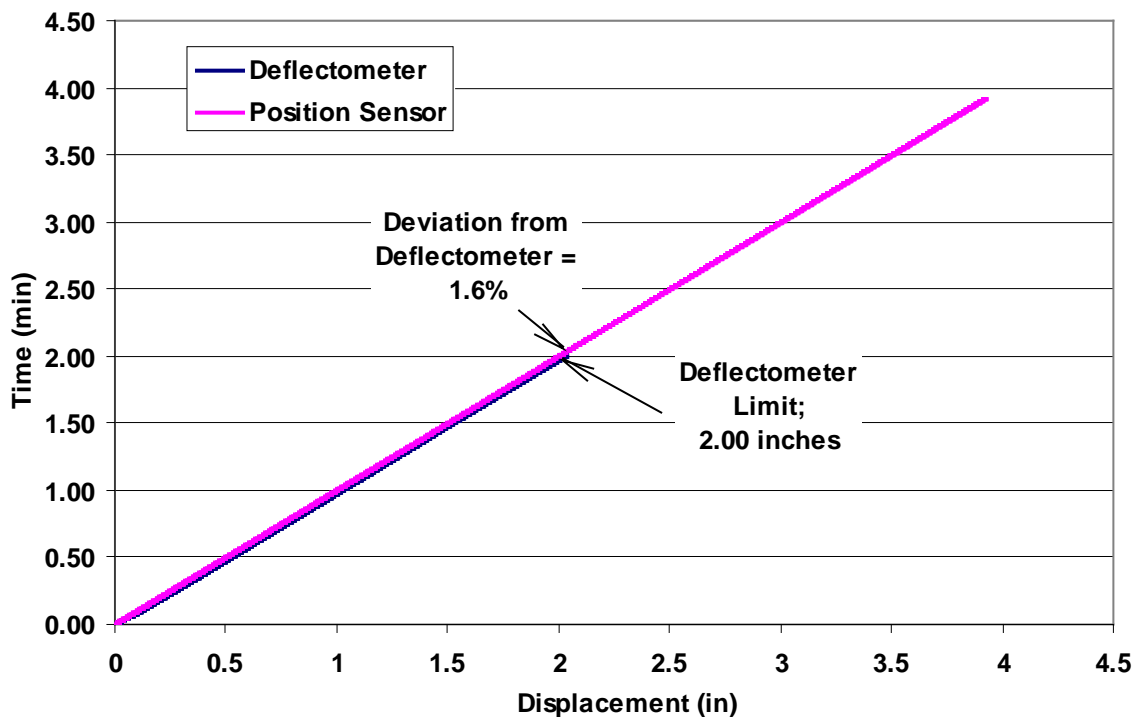


Figure 1. Typical Time Displacement Curve

Apparent strength calculations were based on ultimate failure, which occurred at clearly defined points in each test specimen.

Testing was conducted in three different rounds. Unless otherwise specified, all samples had a nominal thickness of 0.2" with a span of 12" and at least 1" overhang from each loaded edge. A list of sample designations and their significance is included in Appendix A. The different Hardwire tapes are characterized by the type of cord that is used. Figure 2 a) through c) show the different cord types.

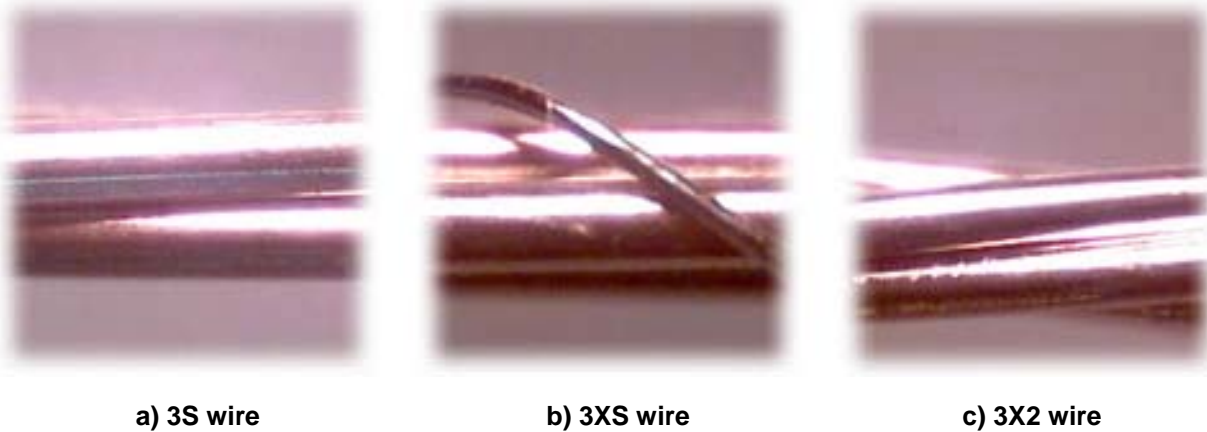


Figure 2. Different Cord Types

The 3S wire cord is made by twisting three identical wire filaments together at a longer than usual lay length. The result is a cord with lower twist angles (amount of twist per unit length) and straighter filaments. The 3XS wire cord is made by twisting three identical wire filaments together at a longer than usual lay length and then over-wrapping the bundle with a single filament. The 3X2 wire cord is made by twisting 5 individual wires together; 3 straight filaments wrapped by 2 filaments at a high twist angle.

Round #1 was primarily a quick comparison of wire bundle (cord) configurations and fiber sizes. All of the Round #1 test samples were fabricated with a Hetron epoxy vinyl ester resin. The purpose of round 1 was to quickly assess the effect of large differences in fiber and cord geometry and to see where to apply future effort. Also key to Round #1 was to find what manufacturing issues might arise from the radically different cord geometries being tested. Note in most testing accomplished in this early round, the key parameter of tape quality and packing density was not optimized due to early difficulties in the cord and tape manufacturing steps. Finally, Round #1 also assessed the feasibility of a very unique "inter-cord" glass steel Hardwire hybrid. In this configuration, the glass tows are placed between successive layers of Hardwire material. The glass effectively fills in the large void regions formed by the large steel wire tows or chords.

Round #2 investigated the effect of silane pretreatments A174 and A1100, on the ultimate strength and failure mode of the unidirectional flexural beams. These steel wire surface treatments are designed to improve adhesion with the resin. A1100 is intended to improve epoxy adhesion, while A174 is intended to improve adhesion with vinyl ester and polyester resins. The A174 pretreatment was used in conjunction with the Hetron resin, while the A1100 pretreatment was used with the Prime 20 epoxy resin. Additionally, HardwireTM/carbon fiber and Hardwire/fiberglass composite laminates were investigated. The Hardwire/carbon fiber

specimens were composed of alternating Hardwire and carbon fiber fabric. The carbon fiber fabrics were unidirectional fabrics made by Hexcel. The fabric areal weight was .0625 lbs/ft², the fiber was Toray T700 and the weight ratio of Hardwire to carbon fabric in the panels was 85%/15% respectively. The 3XSF Hardwire/fiberglass specimens were made with a 675 yield Type 30 Owens Corning glass fiber incorporated into the steel wire cord as shown in Figure 3 in a proprietary co-mingling operation in the cord making process. Ply by ply Hardwire and glass fiber hybrids were also tested made from alternating layers of Hardwire and 13 oz/yard² weft inserted glass unidirectional fabric from Fiberglass Industries.

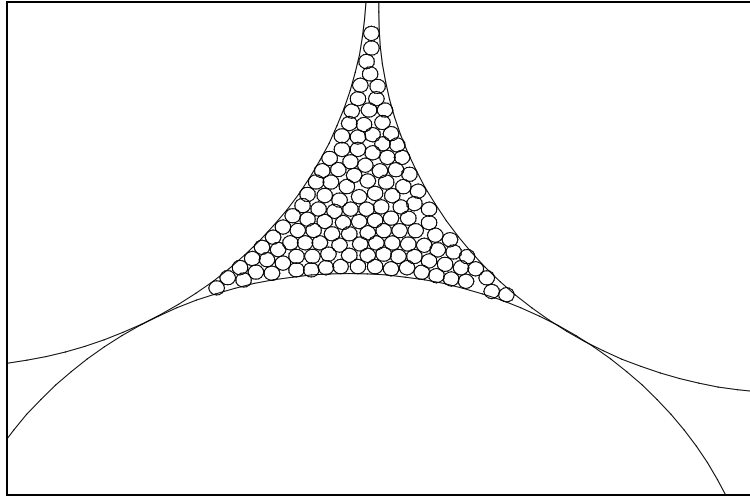


Figure 3. Schematic Comparison of E-Glass Fibers between Steel Wires

The primary purpose of Round #2 was to ascertain if the mechanical bonding of Hardwire cords or the chemical bonding of Hardwire filaments played a role in flexural strength verses control specimens.

Round#3 was a final test of the concepts, and filament and cord geometries developed in the first two rounds. Further, Round #3 benefited from an evolution of techniques and procedures developed during the program that resulted in high quality tape. Sub optimal packing in the previous test rounds resulted in unevenly packed cords, which appeared as intermittent waviness in the test specimen. The cords and tapes were of production quality and served as the final check off before subsequent production scale up. Further, fine-tuning was done on cord geometries and lay lengths to optimize compression properties and processing during the tape making process.

Results

Round #1

In Figure 4 it can be seen that the 3XS and 3XSF cords yielded laminates which were significantly stronger than the 3X2 cord. Note that the 3XS and 3XSF cords have lower twist angles than the 3X2 cord. Additionally, the 3X2 cord failed consistently at the top of the specimen (near the loading nose) in compressive buckling as seen in Figure 5.

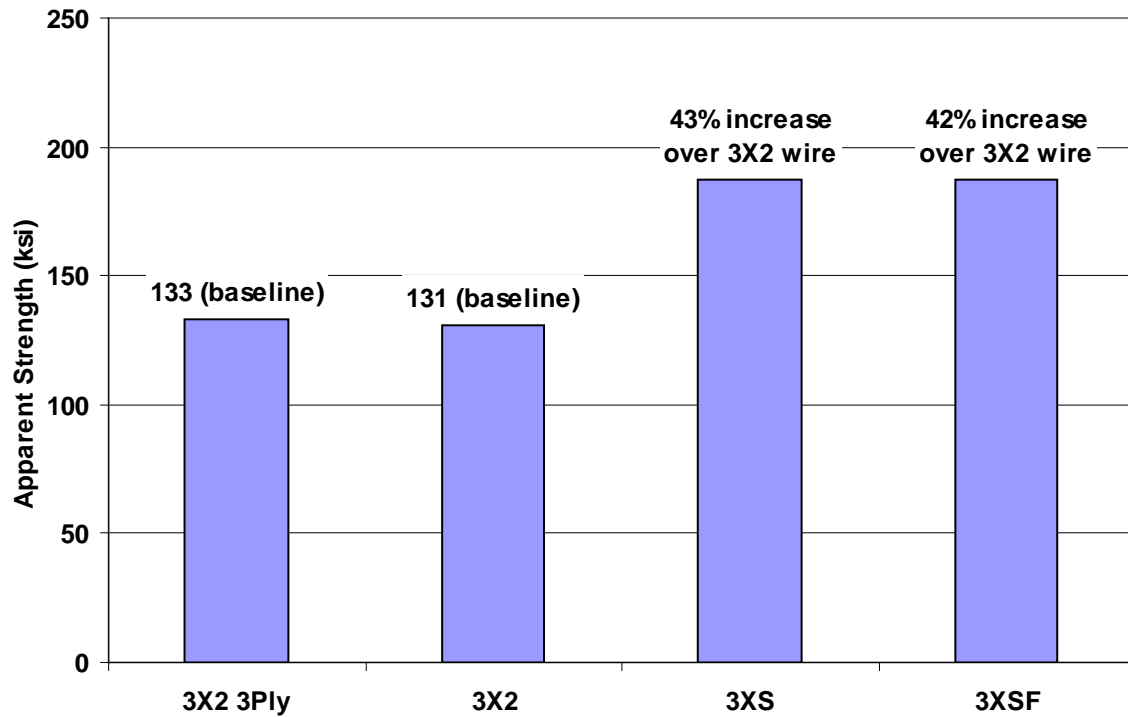


Figure 4. Hardwire-Round 1, Apparent Strength

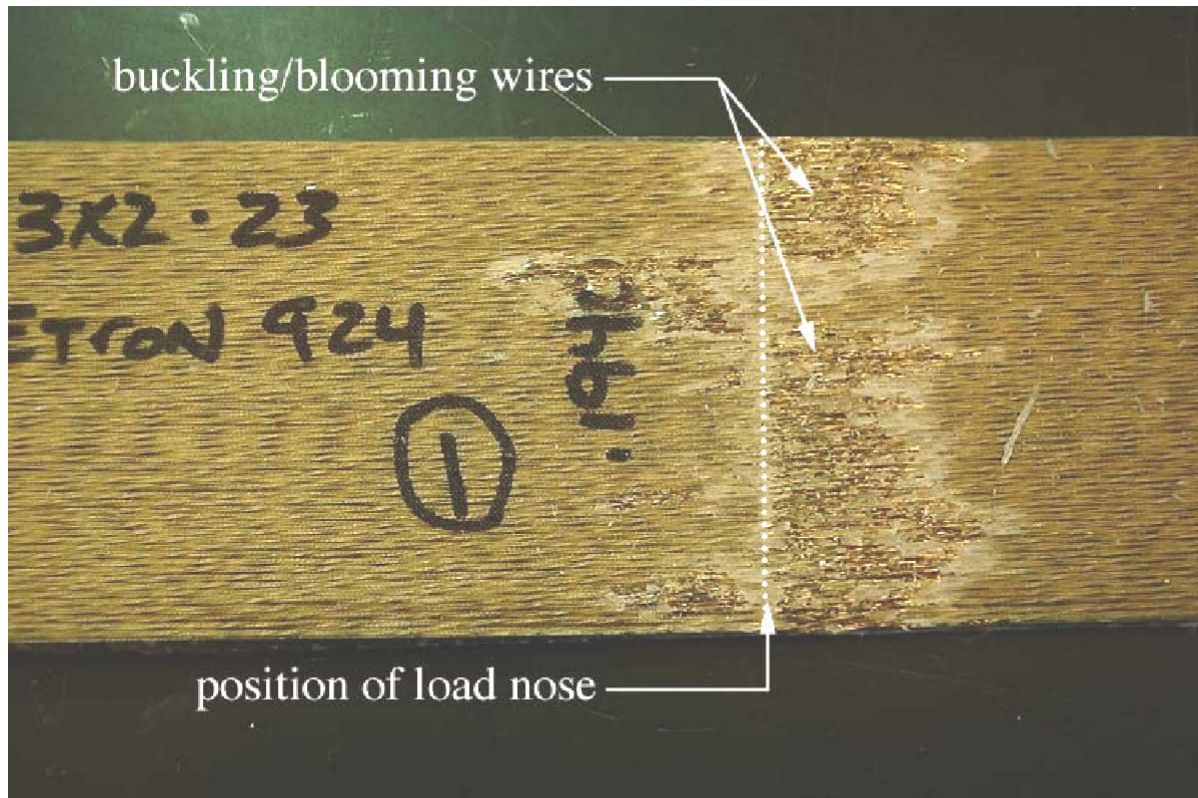


Figure 5. Failure In 3x2 Laminate on the Loading Side Due to Blooming of Wires

The 3S and 3XS laminates failed more consistently in tension and in most tests of the 3S-made beams, failure of the reinforcing wires (Figure 6) occurred as well.

This is consistent with the theory that the poor initial compression results were due to micro buckling, as the lower twist angles in the 3S and 3XS cords provide less opportunity for “blooming” of the cord. Blooming is the effect of the individual wires in a cord buckling outward and away from each other. Figure 7 shows the respective elastic moduli of each sample set. Note there is a significant increase in stiffness in the samples with e-glass hybridized 3XSF cords. This is most likely the result of an overall increase in fiber content because of the addition of the smaller glass fibers, which are incorporated into the steel wire tape to occupy the space between the steel wires. Laminate moduli were lower than expected analytically. One possible explanation for this is that these specimens were fabricated from early manufacturing trials of the Hardwire tape. In the initial development of the Hardwire tape, problems existed with maintaining alignment of the wires as it was being formed into the tape. This resulted in regions of the tape, which had cord waviness. This problem was overcome in subsequent tape production. Another artifact of this fiber waviness or inconsistency in the fiber alignment was the large scatter in flexural strength during the early rounds of testing. Based on these results it was concluded that further optimization of the 3XS and 3S cord and tape configurations would be warranted. This optimized tape, however, was not available for testing in this effort.



Figure 6. Tensile Failure in a 3XS Laminate

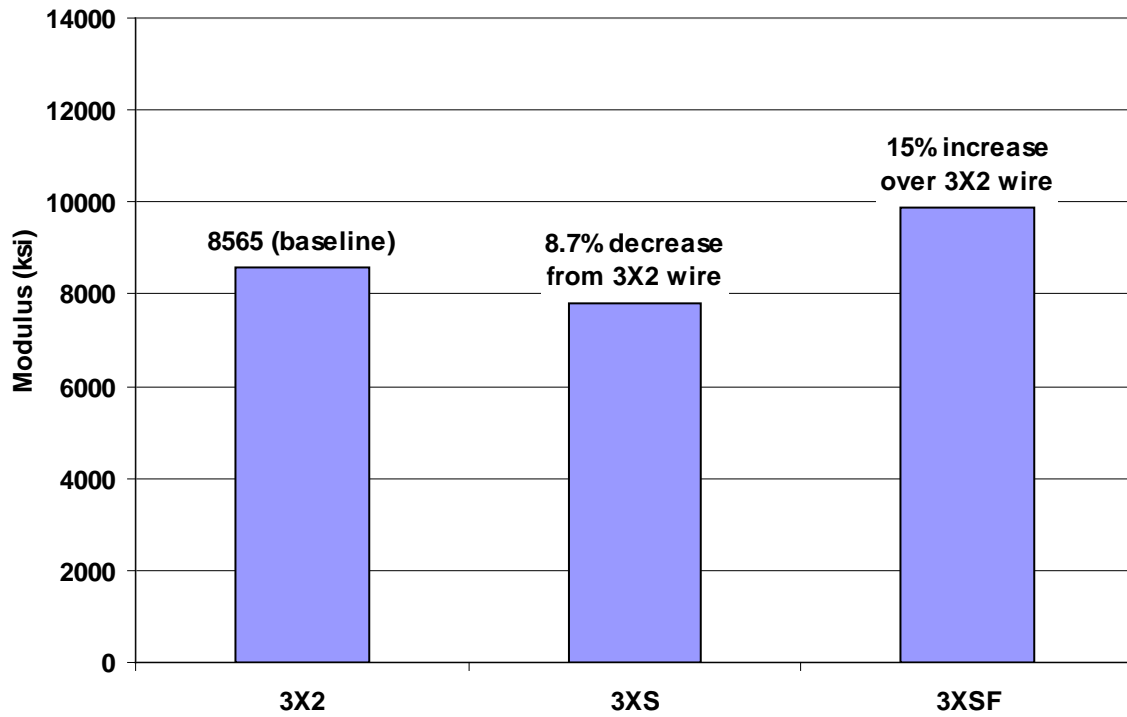


Figure 7. Hardwire-Round 1, Elastic Modulus

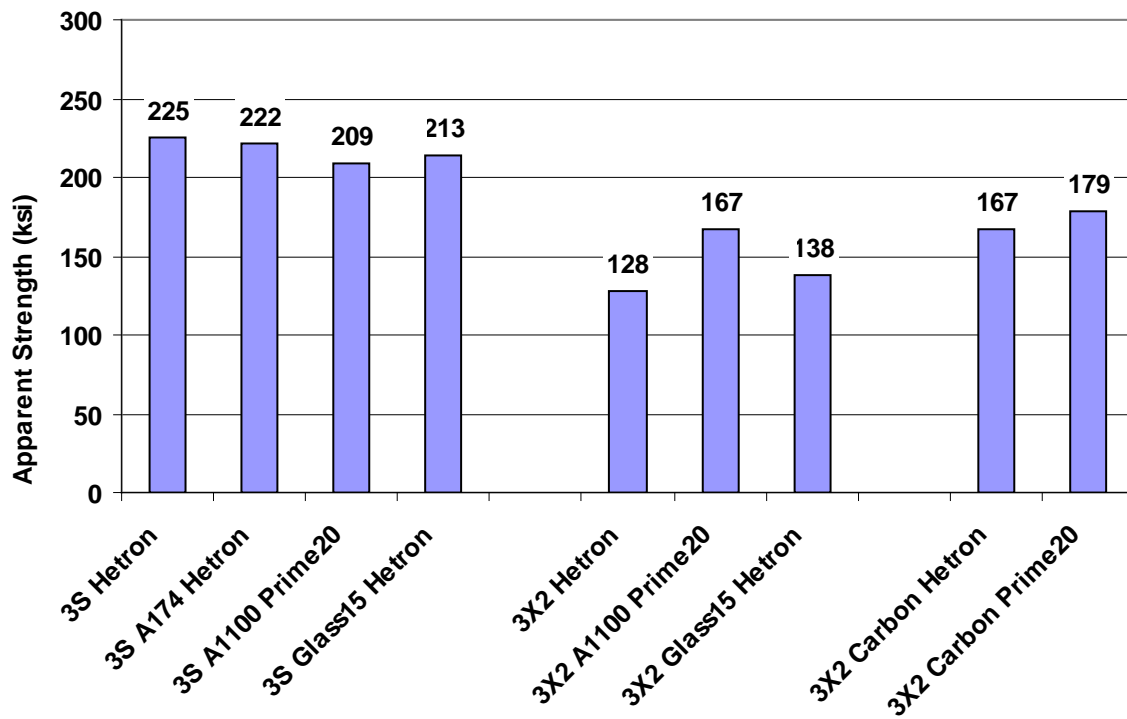


Figure 8. Hardwire-Round 2, Apparent Strength

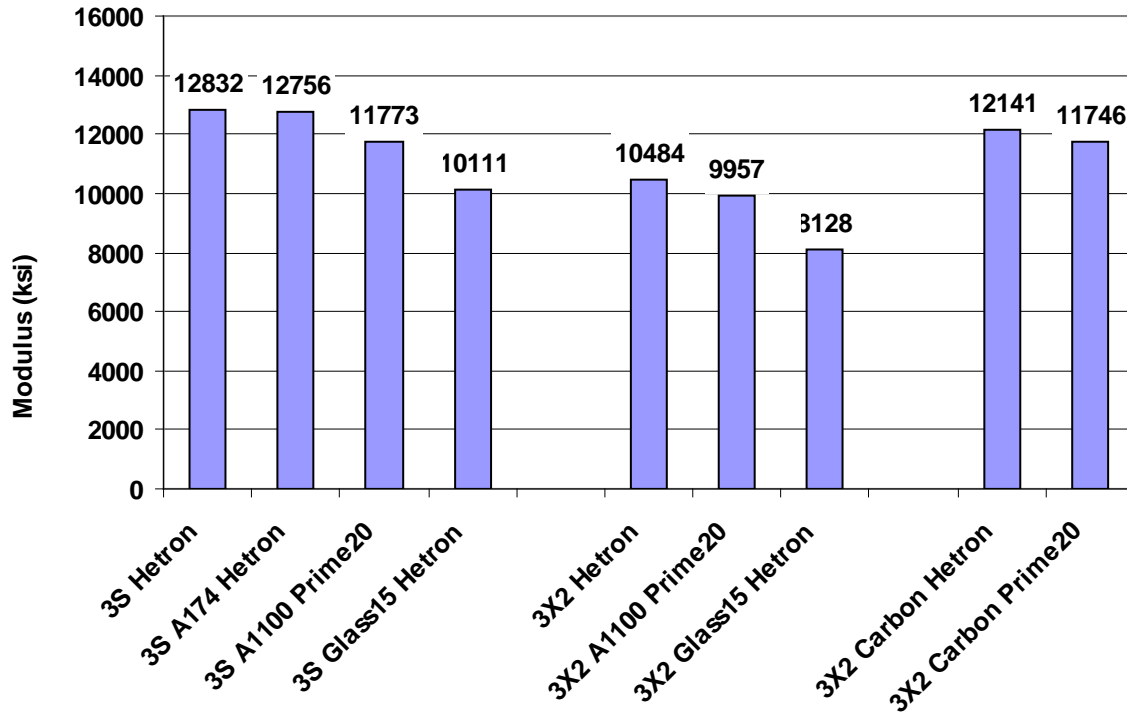


Figure 9. Hardwire-Round 2, Elastic Modulus

Round #2

Figure 8 and Figure 9 show the respective strength and stiffness of each material system. The addition of the A174 primer did not significantly affect the strength or stiffness of the specimen made with the 3S wire. However, the strength of the specimen made with 3X2 was increased by 30%, while the stiffness was decreased by only 5%. When compared with the low decrease in stiffness, the increase in strength and corresponding increase in strain to failure indicates improved wire-to-matrix adhesion, due to the A1100 surface treatment. The 3S panels resulted in stiffness equivalent to the 3X2 Carbon Hetron panels. Similarly, the 3X2/Prime20 and carbon/Prime20 panels were nearly identical in stiffness. The additive fibers have differences in density; so on a specific strength standpoint, the carbon would be the stronger system.

There is one very noteworthy difference in the stress versus strain response between the specimen made with the 3S wire, and those made with the 3X2 wire. Figure 10 shows a typical comparison of the different material systems tested in Round #2. It is seen here that the 3S wire specimens experienced an apparent ductile region beyond a poorly defined yield point. This apparent ductile region could present some significant advantages in the areas of impact, blast resistance and non-catastrophic failure mode over traditional composite materials. A 0.2% offset yield criteria was used to determine the apparent yield strength of the 3S Hetron material as shown in Figure 11. Similar to the laminates made with 3XS and 3XSF, the laminates made with the 3S wire failed consistently at the bottom of the specimen, in tension. Failure in tension indicates that there is very good adhesion and the fibers were able to develop their full tensile strength.

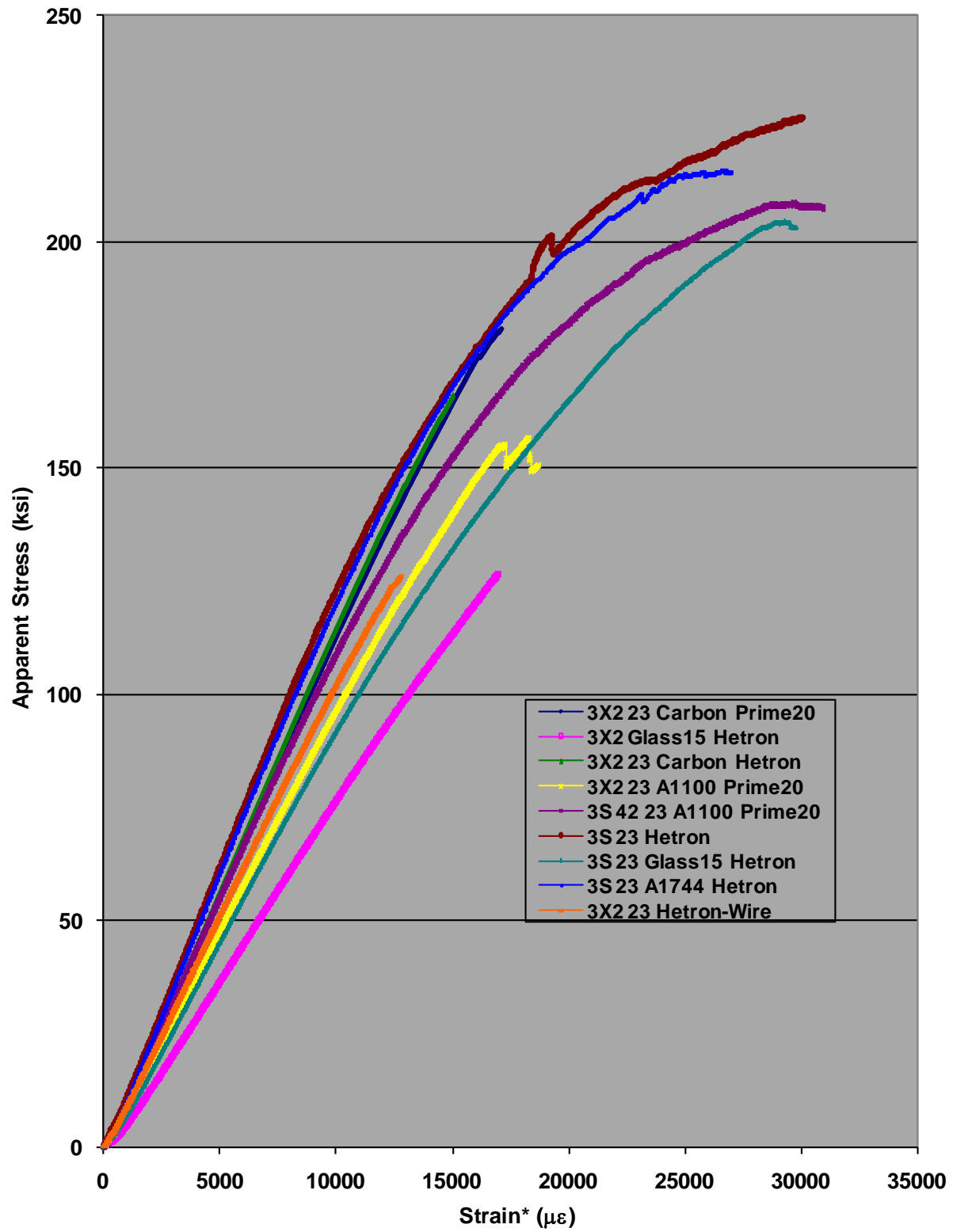


Figure 10. Hardwire Three-Point Bend – Comparison

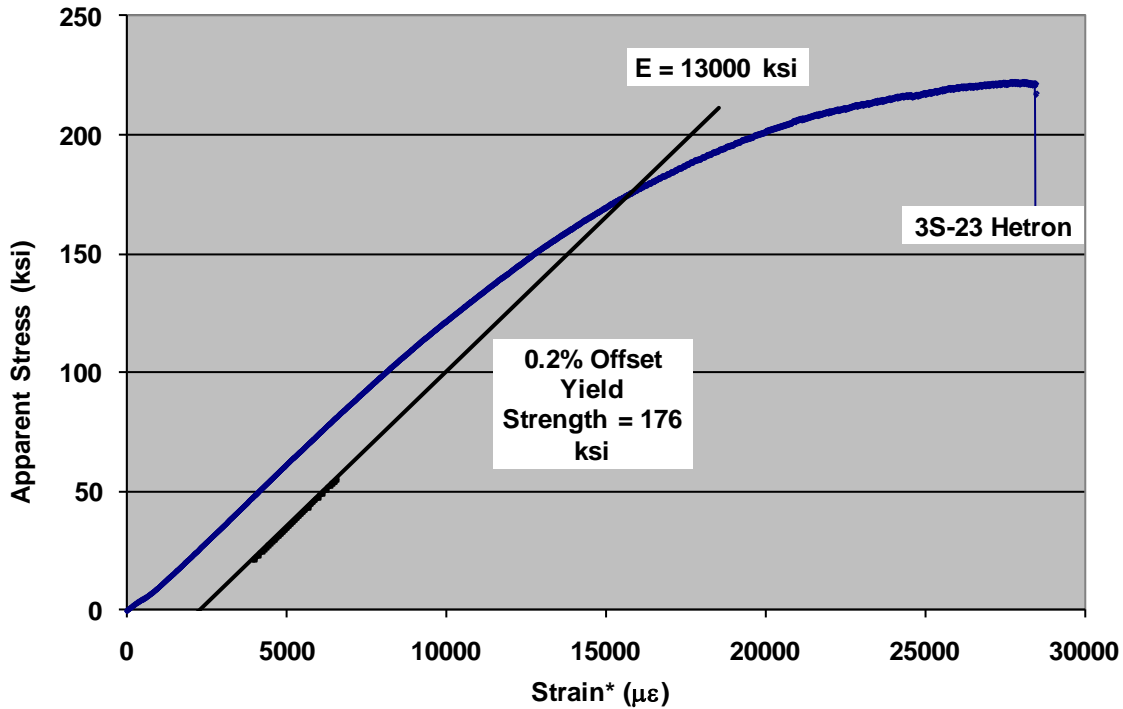


Figure 11. Hardwire Round-2, Behavior to Failure

Round #3

The relative strengths and moduli for Round 3 can be seen in Figure 12 and Figure 13, respectively. The results showed improvements over previous material trials due primarily to material quality and consistency. Fine-tuning on lay length showed the lay lengths tested were still well within the range to produce high compressive strengths. Further, comparison of the medium and long lay lengths (ML and LL, respectively) show that the ability to make high quality tape was as much a factor as the small differences in lay length in the actual samples. In fact, there was no significant difference between the ML and LL for the VE942 system, while increasing the lay length beyond a certain point resulted in decreased strength (-8.6%) and elastic modulus (-18%) in the Jeff18 modified resin system.

It was noted from correlations between single filament adhesion testing (as tested and reported by Hardwire, LLC) and flexural testing that minimum levels of adhesion (500 psi shear strength) are necessary to produce composites which perform well in flexural testing. Single-fiber pullout tests were run with a method developed by Hardwire, LLC. The test consisted of a shallow pool of resin where two single .35mm brass-coated control or brass-coated with primer system wires were inserted into 1/2" of liquid resin. After a room temperature gel and subsequent post cure, the opposing wires were pulled in an Instron mechanical testing system and peak failure was recorded. Test gauge length (the width of the shallow pool of resin), wire surface area and peak load were used to calculate pull out shear strength. Primer systems, resin types and resin additive systems were explored to optimize single-fiber, pull-out shear strength. A picture of the specimens is shown in Figure 14.

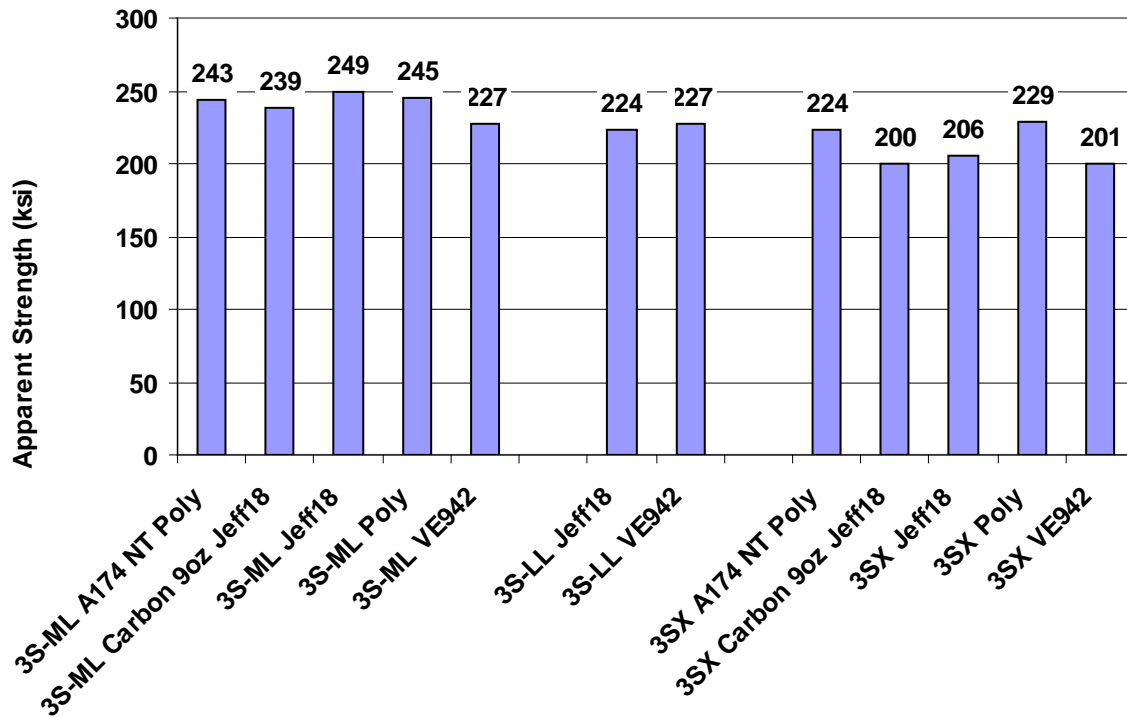


Figure 12. Hardwire-Round 3, Apparent Strength

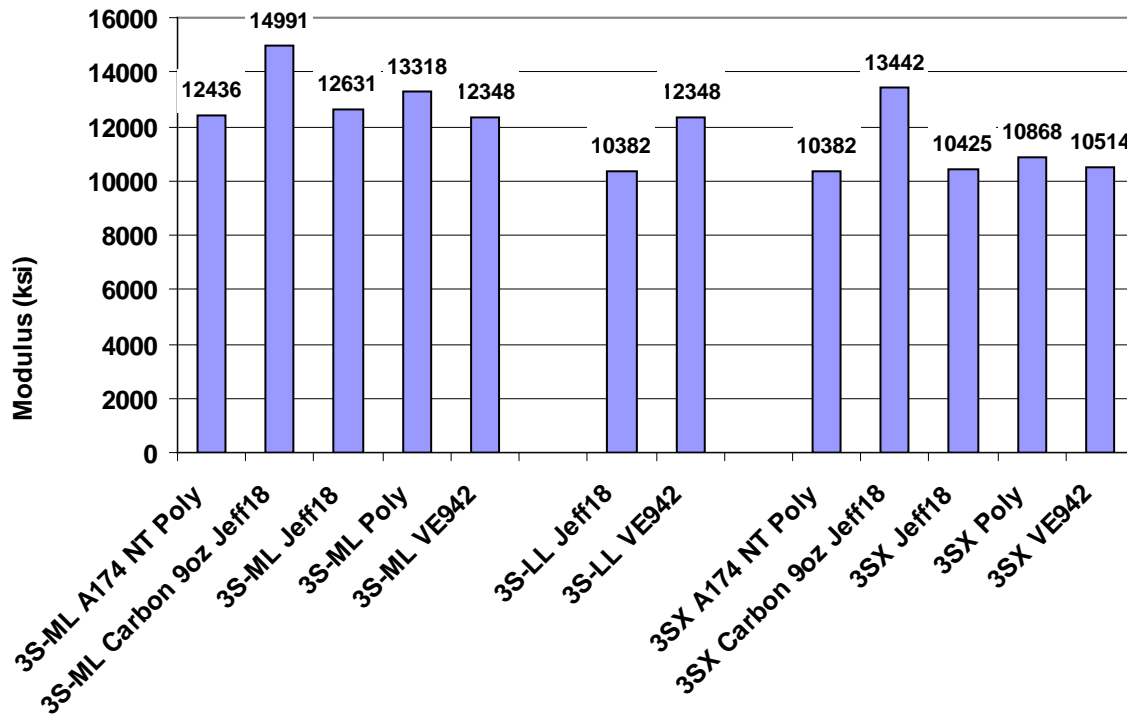


Figure 13. Hardwire-Round 3, Elastic Modulus

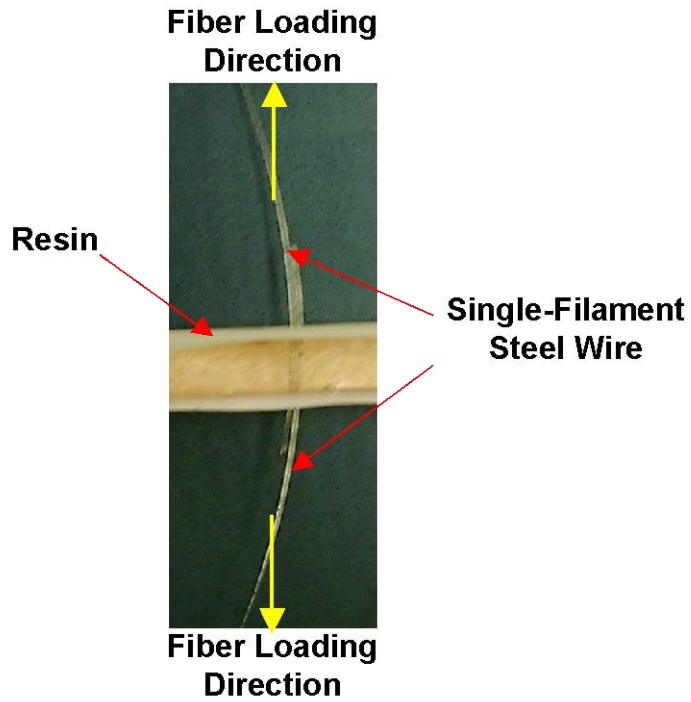


Figure 14. Fiber Pull-out Test to Assess Fiber/Matrix Adhesion



**Figure 15. Post-Testing Images of (from left to right)
3S-LL Hetron, 3S-ML Hetron, 3XS Hetron, 3XS Polyester**

It was further noted that at single filament adhesion levels above 2500 psi (adhesion levels consistent with Jeffco adhesion modified epoxy), composites were produced which showed excellent strength and modulus results with no acoustic emissions during testing and little matrix cracking during testing as seen in Figure 15. It should be noted that the increased region of whitening in the 3S Hetron and 3X2 Hetron specimen was also accompanied by increased acoustic emission during testing.

It is believed this lack of emission correlates to lack of fiber/resin interface failure and will therefore result in structures with superior long-term durability. Adhesion levels in the 1200 psi range (consistent with VE resin systems) showed some acoustic emissions, yet produced excellent and repeatable flexural strength and modulus results.

Conclusions

In general the 3S and 3XS Hardwire cords resulted in improved flexural strength and modulus of the steel-wire reinforced laminate beams compared with beams made using the 3X2 wire cords due to increased wire density, straightness (lay length) and increased filament diameter.

While increasing lay length in the 3S improved the strength over the 3X2 wire, increasing the lay length to a greater degree resulted in processing difficulties and inconsistent tape quality. The substandard tape quality was reflected in the decreased mechanical properties of the long-lay length cords, as compared to the mid-lay lengths. Improvements in processing conditions were also demonstrated by the increased cord count in the 3S and 3XS between round 1, 2 and 3.

Of particular interest was the apparent ductile region exhibited by the laminates made with the 3S wire. Ductile failure is not characteristic of traditional composite materials and may present the potential for improved ballistic and or blast protective properties, although these aspects were not tested or validated within the scope of these analyses. Since the 3S wire has a lower tensile strength than the 3X2 wire, it is likely that the increased flexural strength observed in the 3S wire is due to the ductile behavior of the 3S specimen, indicative of a greater degree of load sharing within the beam. Additionally, the change in failure mode, from compressive buckling to tensile failure may also indicate improved compressive performance of the laminates.

Finally, it should also be noted that none of the Hardwire test specimens resulted in complete or catastrophic failure typical of traditional high stiffness unidirectional composite materials. In each test, the initial failure was limited to the surface wires (either compressive buckling or tensile fracture), leaving the bulk of the material relatively intact. This is an attractive property for primary or critical structures where post-damage structural integrity is needed.

Suggestions for Future Work

It is suggested that the compressive strength of high-modulus steel wire reinforced laminates be measured directly. Because of the relatively large size of the wire filaments, as compared with carbon or glass fibers, end-loaded compression tests result in consistent end effect failures. Shear loaded compression tests will likely yield poor shearing effects, due to the high strength of the composite material in comparison to the low strength of the matrix. Either a large specimen tabbed compression test, or a combined end/shear loading test approach may suffice.

A direct measure of strain within a beam during a three-point bend test may give a more definitive measure of strain distribution within a specimen. Either embedded strain gages, or a full-field optical strain technique may be appropriate.

Finally, environmental conditioning testing, including anodic corrosion should be investigated. Since Hardwire may be of interest to naval applications for primary structures, it is important that the corrosion characteristics of this material be identified.

Appendix A

3 X 2 23 3ply

Vendor-defined terminology:

3X2 is the chord type. It consists of 3 straight filaments (0.35mm diameter) wrapped by 2 filaments at a short twist length (18mm), which results in a high twist angle. The number following the chord designation (usually 23) is the tape density. Indicating that there are 23 chords per inch.

3S is a 3X2 that has been modified so that the 2 wrapping wires are at a lower twist angle (42mm twist length) and the 3 straight wires have larger diameters (0.48mm).

3XS is similar to the 3S, except that it has a wrap wire around the bundle. The wrap wire is intended to improve adhesion via by mechanical advantage. It also improves shear performance.

3XSF is the 3XS hybridized with fiberglass. The fiberglass is commingled with the steel filaments and is intended to improve the composite elastic modulus, buckling strength, and transverse strength, with respect to non-hybrid 3XS.

A174 and A1100 are silane pretreatments designed to improve adhesion. A1100 is intended to improve epoxy adhesion, while A174 is intended to improve adhesion with VE and PE resins.

Prime20® is an SP epoxy resin that is considered to have “medium” adhesion to the wire.

Hetron® is a high stiffness corrosion resistant epoxy vinyl ester resin.

The glass and carbon designations indicate samples that were fabricated as a laminate composite, consisting of steel wire lamina, and either fiberglass, or carbon fiber lamina.

